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SOLID FILM LUBRICATION RESEARCH

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For

Air Force Aero Propulsion Laboratory
Research and Technology Division
ATTN: APFL
Wright-Patterson Air Force Base, Ohio 45433

FOREWORD

This report was prepared by the Westinghouse Electric Corporation, Westinghouse Research Laboratories, Insulation & Chemical Technology Department, Beulah Road, Churchill Borough, Pittsburgh, Pennsylvania 15235, under USAF Contract No. AF 33 (615)-2618. The contract was initiated under Project 3145, "Dynamic Energy Conversion Technology," Task 314502, "Solar Dynamic Power Units." The contract is being continued under Project 8128, "Power Conversion Conditioning and Transmission Technology," Task 812802, "Mechanical Power Transmission and Control and Project 3044, "Aerospace Lubrication," Task 304402, "Advanced Propulsion Lubrication Engineering." The work is being administered under the direction of the Air Force Aero Propulsion Laboratory, Research and Technology Division, with Mr. J. S. Cunningham acting as project engineer. Accordingly, questions relative to this work may be directed to:

Air Force Aero Propulsion Laboratory
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This report covers work conducted from 1 December 1966 to 1 March 1967.

Approved for:
Westinghouse Electric Corporation

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ABSTRACT

This report describes progress during the seventh quarterly period in a program designed to develop a solid film lubricated ball bearing system capable of operation under high speed, high temperature oxidizing conditions. The program's ultimate goal is long-term ball bearing operation at 1500°F and speeds of 10,000 to 30,000 rpm under atmospheric conditions simulating sea-level to 200,000 ft altitudes. A second program objective is to provide parametric design data relating the operating life, load, bearing size, speed, temperature and environment of these bearing systems.

In the materials development area, this report describes further efforts in improving the high temperature friction-wear characteristics of unique self-lubricating composites that are both physically and chemically capable of functioning as load-bearing surfaces in an extreme temperature-oxidizing environment. The composites are composed of solid lubricants, such as WSe_2 and/or WS_2 that have been combined with a gallium-indium alloy.

In the area of functional testing, the results of thirty-nine tests on 204 ball bearings that were evaluated during this reporting period are described. The bearings were operated at temperatures up to 900°F and speeds of 10,600 and 21,500 rpm. Two significant results obtained during this reporting period are the operation of (1) a 204 ball bearing in 600°F-air at 10,600 rpm for a period of 215 hours, and (2) an identical bearing system at 10,600 rpm in a 900°F environment simulating an altitude of 240,000 ft for 66 hours. In both cases the bearing carried a 50 lb thrust/50 lb radial load.

I. INTRODUCTION

Proper lubrication is a prime requisite for the successful operation of any load-bearing surface that undergoes a relative motion between itself and a second component of a system. But, when the load-bearing surface is exposed to a high-temperature oxidizing environment, the lubrication problem is greatly complicated by the effect of environment on the lubricant. Two major effects result from such an environment: First, there is a loss of conventional lubricants through evaporation and chemical decomposition. Secondly, through an oxidation process, solid lubricants are transformed to relatively abrasive metal oxides. The resulting substantial increase in friction eventually brings about the catastrophic failure of the load-bearing system by means of a wear mechanism.

This program is designed to develop solid film lubrication systems capable of long term operation in atmospheres characteristic of those from sea level to 200,000 ft, at temperatures from -45 to +1500°F, and at speeds approaching 30,000 rpm. The program has two major objectives:

1. To optimize the physical properties of certain unique composites and thereby provide materials that are both physically and chemically capable of functioning as self-lubricating load-bearing surfaces in an extreme-temperature oxidizing environment. A unique technique discovered at the Westinghouse Research Laboratories for imparting mechanical strength and oxidation resistance to composites of high solid lubricant content is being investigated in attempts to achieve this goal.

2. To functionally evaluate the performance of high-speed ball bearings utilizing these composites as self-lubricating retainers. Parametric design data relating the operating life, load, bearing size, speed, temperature, and atmospheric environments is being obtained.

The materials optimization portion of the overall effort has emphasized the evaluation of candidate materials with respect to friction coefficients, wear resistance, mechanical strength and oxidation resistance. The effect of elevated temperature, oxidizing environments on the friction-wear characteristics of candidate composites under high sliding velocities is also being determined.

The functional test portion of the program, in a step-wise approach, is designed to demonstrate long-term operation at successively higher temperatures of 600, 900, 1200 and 1500°F.

II. EXPERIMENTAL

A. Material's Support Program

1. High Temperature-High Speed Friction/Wear Measurements

As was reported previously[1], high temperature studies of the WSe_2 and WS_2 composite amalgams had shown them to have excellent friction-wear characteristics over a 1200°F temperature range in an air environment. Since differences in wear rate for both materials between 75 and 1000°F were less than a factor of two, it was anticipated that a successful 600°F bearing system (> 100 hrs life) would function satisfactorily at 900°F, with its useful operating life reduced by a factor of about two. Functional test results at 900°F on the 600°F bearing system, however, did not verify this hypothesis. Where an average life of 200 hours has been demonstrated on the 204 system at 600°F, (Runs 148 & 149, this report), the average life on the same system at 900°F was found to be ~20 hours.[2] The two prime possibilities that might explain this behavior were:

a) "Premature" bearing failures at 900°F - 10,600 rpm were being caused by some bearing design parameter as yet not adjusted for 900°F operation. These parameters included internal bearing clearance, cage fits, and bearing material. Insufficient internal bearing clearance was, in fact, responsible for premature bearing failures in the earlier 600°F work.[1]

b) High temperature friction-wear tests performed on the materials were not adequately simulating the load-speed combination imposed on the lubricating material under actual operating conditions. Furthermore, that under these operating conditions, higher wear rates are an inherent characteristic of the basic tungsten diselenide-gallium/indium composite when temperatures of 900°F are reached.

To explore the second possibility, a series of high temperature friction-wear experiments were performed under the same unit loading conditions (80 psi) used previously but employing surface speed conditions more closely approximating those experienced by the self-lubricating cage in an actual bearing operating at 10,000 rpm. These surface speed conditions had recently been obtained from work[3] performed by Mr. J. S. Cunningham, project monitor of this program at Wright-Patterson Air Force Base. The data proved extremely valuable in establishing the new test conditions. These revised test conditions are listed below and compared with those used previously.

	Original Conditions	Revised Conditions
Load - psi	80	80
Surface Speed - fpm	230	2550
Temperature - °F	75 500 1000 1500	75 600 900 1250

A comparison of the friction-wear characteristics of the $80WSe_2$-20 GaIn composite under these two different surface velocities are given below:

	230 fpm - 80 psi		2550 fpm - 80 psi	
	Friction Coef.	Scar-mm	Friction Coef.	Scar-mm
75°F	0.19	1-3/4	0.06	3
500°F	0.02	1	----	-
600°F	----	-	0.04	5
900°F	----	-	0.04	11
1000°F	0.25	2-3/4	----	-

It is quite clear from these data that the WSe_2-GaIn composite suffers an extremely sharp increase in wear rate <u>under high surface speed conditions</u> as its operating temperature increases from 600 to 900°F. This sharp increase in wear rate is not experienced when operating temperatures are increased from 75 to 600°F. It was concluded from these data that bearing failures experienced at 900°F after approximately

20 hours operation are caused by this wear characteristic of the basic WSe_2 amalgam. This conclusion is also supported by functional test data reported later in this summary exploring the possibility that some bearing design parameter was responsible for premature 900°F failure.

In view of these results, no further functional tests were initiated in a 900°F-air environment on ball bearing systems utilizing the basic tungsten diselenide composite. Instead, efforts were concentrated on either modifying the WSe_2-GaIn composite or substituting other solid lubricants in the composite in order to improve its high surface speed wear resistance in the 900°F temperature range.

2. Tungsten Disulphide Synthesis

It had not as yet been determined if the 900°F-high speed composite wear characteristic described in the previous section was inherent to the WSe_2-GaIn material or caused by an increased oxidation rate of the lubricant film established on bearing components. In an attempt to answer this question, a functional test was performed on a 204 bearing system in a vacuum environment of 1×10^{-2} torr at 900°F. The bearing was equipped with a retainer of 80% WSe_2-20% GaIn (wt) and operated at 10,600 rpm under a 50 lb thrust/50 lb radial load. While the results of this test will be described in detail in a later section of this report, one point was brought out by the experiment that was quite pertinent to the material's support program. This was the fact that the bearing operated successfully for a period of 66 hours. This bearing life is approximately four times greater than that achieved on the same bearing system-operating under identical conditions-in an air environment. The result strongly indicated that accelerated oxidation of the lubricant film at 900°F was playing a major role in causing high wear rates and short bearing life under high surface speed conditions.

In view of this development, the decision was made to investigate the possibility of (a) substituting the more oxidation resistant tungsten disulphide for tungsten diselenide, and (b) incorporating various quantities of WS_2-GaIn in the basic WSe_2-GaIn composite. Two major obstacles hindered this approach. First, considerable difficulty had been experienced in

fabricating pieces employing WS_2 as the lubricant. Regardless of pressing conditions, bodies fabricated from commercial tungsten disulphide would delaminate either on die stripping or during the firing cycle. It was discovered, however, that this problem could be eliminated by employing tungsten disulphide synthesized in this laboratory. The technique used to synthesize the lubricant was identical to that used for tungsten diselenide.[4] The authors cannot at this time offer an explanation for this observed difference in behavior between commercial WS_2 and that prepared in this laboratory. All data on WS_2 composites reported from this point on, however, pertain to materials employing Westinghouse synthesized WS_2.

The second problem involved in the use of tungsten disulphide gallium-indium composites has been the inability to obtain adequate mechanical strength in these materials. A discussion of this problem and a tentative explanation for the low mechanical strength of WS_2 and MoS_2 composites was presented in the 4th quarterly report. Briefly, it was shown that unlike tungsten diselenide, tungsten disulphide does not interact with gallium/indium at the 450°F temperature level involved in the curing cycle. There is strong evidence from a Westinghouse in-house program that this reaction is necessary before high strength can be obtained in the piece. More recently, this in-house program has further demonstrated that a high degree of crystal orientation in the lubricant molecule-even in the case of tungsten diselenide-can result in the elimination of this reaction with subsequent loss in strength. A technique widely used for achieving a high degree of crystal orientation in these solid lubricants is to subject the material to an extreme temperature anneal, the maximum temperature required being a function of the material itself. Figure 1 shows the effect - in the form of DTA analyses - of highly orienting the WSe_2 molecule on the tungsten diselenide-gallium/indium interaction. It will be noted that no reaction occurs at 450°F. A direct result of the loss of this reaction is a reduction in the (1100°C) WSe_2-GaIn compressive strength to $<$ 2000 psi. In comparison, the average compressive strength of the standard (750°C) WSe_2-GaIn is 20,000 psi.

In an effort to apply this principle to the program's advantage, a study was initiated to determine the effect of annealing temperature during lubricant systhesis on the mechanical properties of 80% WS_2-20% GaIn (wt) composites. A series of four specimens each were fabricated under identical conditions regarding temperature and pressure but employing tungsten disulphide powder that had been annealed during its synthesis at three different temperatures; namely, 1380, 930, and 750°F. The results of compressive strength tests and selective friction-wear experiments on these specimens are given in Table I. While no effect on mechanical strength was observed by annealing the lubricant at 930°F instead of 1380°F, a 100% increase in mechanical strength was achieved when the annealing temperature was further reduced to 750°F. In addition, it was noted that the reproducibility of compressive tests on these specimens was considerably better than those composites using higher anneal temperature lubricant.

A second series of experiments was performed to investigate the effect on compressive strength of the length of ball-milling time to which the WS_2-GaIn was subjected. The results, shown in Table I, revealed that an additional 25% increase in strength in the 750°F material was obtained when ball-milling time was reduced from the original 60 minutes to 30 minutes. A further reduction to 15 minutes resulted in a 100% increase in the strength of the 930°F anneal material as well. Again, the reproducibility of these results was quite good. Except for the results discussed in the next section, therefore, all future composites incorporating tungsten disulphide will employ the Westinghouse synthesized lubricant annealed at 750°F. The tungsten disulphide-gallium/indium aggregate will be prepared according to the following procedure:

Mill Size	- 1 quart ball-mill containing 50 3/4" x 1" rollers
Rotation	- 72 rpm
Charge	- 600 gms
Rolling Time	- 30 minutes

3. Fillers for WS_2-GaIn Composites

In conjunction with the work described in the previous section, an attempt to increase the mechanical strength of the WS_2-GaIn composite through the use of tungsten or tungsten diselenide-gallium/indium fillers was undertaken. Since the results of the work described in the previous section was not yet completed, the WS_2 used in this study was annealed at 930°F and the aggregate combined by ball-milling for a period of 1-1/2 hours. The mechanical properties of all specimens were therefore not as high as one might expect had the material been prepared under the optimum conditions outlined above. For purposes of comparison, however, the test results presented in Table II, proved useful. They demonstrated that neither the incorporation of various concentrations of WSe_2-GaIn in the WS_2-GaIn aggregate nor the use of tungsten powder as a filler brought about any improvement over the mechanical properties of the basic WS_2-GaIn composite. In addition, it will also be noted that the pressure used in fabricating the specimens had no significant effect on specimen strength over a 100,000 psi range.

Table III presents the results of experiments investigating the use of 20% (wt) concentration of tantalum and molybdenum as a filler in WS_2-GaIn composites. Filler particle size was -325 mesh and the lubricant-alloy mixture was prepared according to the revised procedure described in section 2 of this report. The study was designed to determine the effect of both the temperature and pressure of fabrication on composite properties. The mechanical strength of these composites was substantially higher (~2x) than those incorporating tungsten or WSe_2-GaIn as fillers. It must be pointed out, however, that in general this strength was not significantly higher than that obtained on the basic WS_2-GaIn material when the material is prepared according to the revised synthesis and ball-milling procedure. Subsequent data did in fact show that the major portion of the observed improvement in strength in filled composites was probably due to this new procedure.

In Table IV, the results of work performed to determine: (a) the possibility that the increased strength obtained in the Mo and Ta filled composites was due to WS_2-GaIn preparation and not the use of fillers,

and (b) the effectiveness of copper powder as a filler are shown. Using WS_2 annealed at 750°F and WS_2-GaIn aggregate ball-milled for 30 minutes only, a second group of tungsten filled composites (20% wt W) was prepared under the same conditions as those listed in Table II. A comparison of the compressive strengths of these two groups of pellets revealed that the group employing WS_2-GaIn prepared under the revised procedure exhibited mechanical properties twice as high as the original group. In addition, this higher compressive strength was essentially the same as the basic WS_2-GaIn composite, indicating that no significant improvement in strength is gained by the incorporation of 20% (wt) tungsten powder. This conclusion applies in the case of molybdenum and tantalum fillers as well. A similar situation was found to exist when attempts were made to increase composite strength through the use of copper fillers. As shown in Table IV, specimens incorporating 20% (wt) copper powder in the WS_2-GaIn aggregate again resulted in compressive strengths of the finished pieces in the same range(15000 psi) as the unfilled material. At this point in the program, therefore, all attempts to increase the strength of the WS_2-GaIn composite through the use of fillers (W, Mo, Ta, & Cu) had been essentially unsuccessful, although the basic WS_2 composite had been improved mechanically by a factor of two.

It was found, however, that the incorporation into WS_2-GaIn of a blend of two of these fillers provided a result directly opposite to that observed when one filler only was used. Using a 1:1 ratio (wt) of tungsten and copper powders, a series of specimens were prepared over a 100,000 psi pressure range. The Cu-W filler was used in a concentration of 20% (wt), the same quantity as was used in the composites previously discussed in which a single filler was employed. The results of friction, wear, and compressive strength tests performed on these specimens are also listed in Table IV. It will be noted that a maximum compressive strength of 25,900 psi was measured on a WS_2-GaIn composite containing copper and tungsten powders, each in a concentration of 10% (wt). The reproducibility of this result was excellent for a given fabrication pressure. Upon the substitution of WSe_2-GaIn for WS_2-GaIn, the mechanical properties of the composite improve even further to a

maximum of 47,000 psi for a material fabricated at 100,000 psi. It is pertinent to point out here that these high mechanical properties for both WS_2-GaIn and WSe_2-GaIn composites have been achieved without the use of high temperature fabrication. The possibility of further improvements in this property through moderate or high temperature pressing remains.

4. Temperature Effect on High Speed Wear Characteristics

Table V presents a summary of experiments performed to determine the effect of temperature on composite candidates for 900°F operation. All tests were run on a Hohman tester under high surface speed conditions (2550 fpm) and a bearing pressure of 80 psi. Four commercially available materials are included for purposes of comparison. The first two materials listed are the basic WSe_2-GaIn and WS_2-GaIn composites. It will be noted that the WSe_2-GaIn composite exhibits relatively good strength but poor wear resistance at 900°F. Conversely, the WS_2-GaIn composite exhibits excellent wear resistance at 900°F but is weak mechanically. As will be discussed later in the report, this deficiency in mechanical strength results in early bearing failure when the material is used as a self-lubricating retainer at high speeds. It is also evident from the data that (a) as the concentration of WSe_2-GaIn increases in WS_2-GaIn the high temperature wear resistance of the composite decreases, and (b) little if any advantage is realized by the use of tungsten powder as a filler in either basic material. It is encouraging to note that the high strength Cu-W filled composites possess a wear rate at 900°F that is well within the tentative limit that has been established (~5mm, which is equivalent to that of the WSe_2-GaIn composite at 600°F). Figures 2, 3 and 4 present the wear characteristics of these materials as curves plotting wear rate as a function of temperature.

5. Hot Pressing WS_2 GaIn Composites

During this reporting period a program was also initiated to determine the effect of hot pressing on composite strength and lubricating characteristics. Four samples have thus far been prepared from a WS_2-GaIn

composite containing 20% (wt) tungsten powder as a filler. The specimens were first green-pressed at room temperature and 50,000 psi. Following their preparation they were cured at 450°F for 15 hours. Finally, each specimen was individually charged to a graphite die and compressed under argon at 3000 psi and various temperatures. The results are given below:

Material - 80% WS_2 GaIn - 20W

Pretreatment

a) Fabrication-R.T. - 50,000 psi

		#1	#2	#3	#4
b)	Cure	450°F-15 hr	450°F-15 hr	450°F-15 hr	St'd (450°, 600°, 900°)
c)	Hot Press Temp-°F	1100	1380	1560	1380
d)	Hot Press Load-psi	3000	3000	3000	3000
e)	Duration - min	30	30	30	30
f)	Friction Coef.*	0.12	0.19	0.19	0.15
g)	Wear* - gms/hr	0.002	0.002	0.002	0.002
h)	Compressive Strength - psi	7240	6570	5610	7832

* 500 psi - 70 fpm - 75°F

While hot pressing under the above conditions did not alter the desirable friction-wear characteristics of this composite, neither did it improve the compressive strength under any of the conditions investigated.

B. Functional Test Program Results

A total of thirty-nine functional tests were performed on the 204 ball bearing system. The tests were made at both 600 and 900°F and 10,600 rpm as well as 600°F and 21,500 rpm. All bearings except one carried a 50 lb thrust/50 lb radial load. Three experiments were performed in a vacuum environment simulating an altitude of 240,000 ft. The results of these tests are summarized in the sections that follow.

1. 204 Bearing System - 600°F, 10,600 rpm

Prior to this reporting period, the maximum life obtained under the above conditions with a 50 lb thrust/50 lb radial load had been 133 hours.

This life had been obtained using the insert-type titanium retainer, shown in Fig. 5, as the lubricating member. Employing the improved, double-shrouded retainer design described in the 4th Quarterly Progress Report and shown in Fig. 6, this performance has now been increased to a 200 hour average operating life. In Run 148 (Table 6), a 204 ball bearing equipped with a double shrouded WSe_2-GaIn retainer operated for a period of 215 hours before failure. In Run 149 the same bearing system-identical except for the use of titanium carbide balls-operated for 190 hours before failure. It is significant to note here that use of the lighter titanium carbide balls did not bring about an improvement in life at 10,600 rpm. Run 150 was performed to determine if the double shrouded retainer was also capable of providing reasonable life under the higher load of 100 lbs thrust/100 lbs radial. A life of 98 hours was achieved before test termination due to roughness. The test had been interrupted after ~70 hours operation due to a power failure. Figs. 7 and 8 are photographs of the bearings from Run 148 and 149 after test completion. An excellent lubricant film was on all bearing components.

Run #151 was the first high temperature vacuum run performed on the improved 204 bearing system. The environment simulated an altitude of ~240,000 ft. The test was performed at 600°F, 10,600 rpm under a 50 lb thrust/50 lb radial load. Despite the fact that oven temperature and not bearing temperature was controlled, a bearing temperature rise of only 20°F was experienced upon test start-up. This differential was maintained throughout the test. Test failure occurred after 50 hours operation and was not caused by bearing failure, but by the fact that one radial weight loosened during the run and was lost at 50 hrs. This run established the fact that solid lubricant-gallium/indium composites retain their ability to lubricate under high-temperature-high altitude conditions.

2. <u>204 Bearing System - 900°F, 10,600 rpm, 50# Thrust/50# Radial</u>

A total of twenty-six functional tests were performed during this reporting period under the above conditions. One of the first objectives

of this group of tests was to determine if some bearing design parameter were causing premature failures at 900°F. It had already been demonstrated that larger internal bearing clearances (Run 140, 4th Quarterly Report) did not improve 900°F life. Through Runs 154, 159 and 160, Table 6, it was shown that neither the use of titanium carbide balls, larger cage clearances between it and bearing components, or bearing design provided an improvement in operating life for the WSe_2-GaIn lubricated system. The most significant run of this particular group of experiments is Run 152. In this particular test, the bearing was operated at 900°F and 10,600 rpm but in a vacuum environment of 1×10^{-2} torr (~240,000 ft). Retainer material was composed of the WSe_2-GaIn composite. The purpose of the test was to determine if the presence of oxygen in the bearing environment was a significant factor in causing the high wear rates experienced by this composite at 900°F under high speed conditions. A life of 66 hours was obtained on the 204 system in this vacuum environment. This life is 3-1/2 to 4 times greater than that obtained on the same system in air and suggests three important points:

a - The present bearing-cage design is capable of providing long life under these higher temperature operating conditions with little or no changes required provided a material of adequate wear resistance is developed.

b - Oxidation is a definite factor in causing the high wear rates experienced at 900°F in the WSe_2-GaIn composites. In the writers' opinion, the critical aspect of this interaction is not that of bulk oxidation of the lubricating body but of lubricant film oxidation, affecting the need - and therefore the rate - of film transfer to metal surfaces requiring lubrication.

c - It is probable that this mechanism, while not as prominent at the 600°F temperature level, does affect system life. Its elimination through a high altitude or high vacuum environment might therefore improve significantly upon the 200 hour life already achieved at 600°F.

The majority of the remaining tests reported in Table 6 were made on 204 bearing systems equipped with self-lubricating materials fabricated from various composite compositions that exhibited acceptable

wear resistance at 900°F on high speed Hohman tests. The low compressive strength of these materials, as discussed in previous sections of this report, becomes obvious as one notes the mode of test failure. In most cases involving WS_2-GaIn composites, test failure was caused by cage or insert fractures and not high wear. The compressive strength of these materials did not exceed 15,000 psi in any of these tests, indicating that a minimum requirement for this parameter under these test conditions is at least 20,000 psi and probably higher. A second cause of failure in those tests using insert-type cages was loosening-with subsequent fracture and loss-of ball pocket inserts. This problem has been eliminated, however, by the use of restraining rings on the outer periphery of the titanium retainer.

Runs 174, 175, 167 and 177 were made on bearings equipped with boron nitride (#174) and Sk-267 graphite retainers. The boron nitride retainer suffered severe wear and quite high running torque during an operating period of only two minutes. Test failure in the case of an unshrouded graphite cage (Run #175) was caused by cage fracture. While the use of a double-shrouded graphite retainer in Run #167 resulted in improved performance of this system, test shut-down was required due to shroud slippage and rough operation. To eliminate the possibility of shroud slippage, Run #177 employed a pinned, LL shrouded graphite cage. A life of 20 hours was obtained before test failure due to cage fracture.

3. <u>204 Bearing System - 600°F, 21,500 rpm, 50# Thrust/50# Radial</u>

A total of nine tests were performed during the past quarter under the above test conditions. A maximum life of 3.5 hours was obtained during this series of tests in Run #168. Test failure was caused by cage instability. The results of this instability can be seen in Fig. 9. It is apparent that localized wear on the inside surface of the retainer, (guiding surface) allowed the titanium shroud to eventually rub the outer ring of the bearing. This contact causes almost immediate test failure at the 21,500 rpm speed level. While cage instability remains the primary cause of bearing failures at 21,500 rpm and 600°F, there was some indication in Runs 165 and 176 that (a) the use of the lighter titanium

carbide balls, and (b) the use of the much lighter graphite cage both appeared to minimize cage instability. Run #165, Fig. 10, is particularly interesting in that the bearing operated for almost 3 hours with no evidence of cage instability found upon cage examination. Contrary to this result, instability was the cause of failure in Run #170 despite the use of TiC balls. The major difference between these runs was the use of one less ball in that test showing instability.

III. CONCLUSIONS

The following conclusions are drawn from experiments performed during the past quarter:

1) High temperature friction-wear tests performed on test materials were not adequately simulating the load-speed combination imposed on the lubricating material under actual operating conditions. Furthermore, that under these operating conditions (2250 fpm), higher wear rates are an inherent characteristic of the basic tungsten diselenide-gallium/indium composite when temperatures of 900°F are reached.

2) The high wear rate of the WSe_2-GaIn composite at 900°F is caused primarily by an oxidation process. This oxidation is occurring in the lubricant film established on bearing components, and not in the bulk retainer material.

3) Tungsten disulphide-gallium/indium composites provide adequate high speed wear resistance in a 900°F-air environment.

4) Up to this point WS_2-GaIn composites have been mechanically weak, with compressive strengths ranging from 6000 to 8000 psi. It has been found, however, that synthesizing the lubricant at temperatures substantially lower than previously used provides a two-fold improvement in WS_2-GaIn materials (15000 psi compressive).

5) Reducing the ball-milling time used to form the WS_2-GaIn aggregate also appears to increase the mechanical strength of the finished piece.

6) The use of a 20% (wt) concentration of Cu and W powders (1:1 ratio) as a metal filler in the WS_2-GaIn composite results in an increase in compressive strength from 15,000 psi to 26,000 psi.

7) The incorporation of the same filler in an identical concentration and ratio in the WSe_2-GaIn composite increases its compressive strength from 20,000 psi to 47,000 psi.

8) An average life of 200 hours has been demonstrated on the 204 bearing system at 600°F, 10,600 rpm and a load of 50 lb thrust/50 lb radial. This life is obtained in an air environment with WSe_2-GaIn as a retainer material.

9) A life of 66 hours has been obtained on the same bearing system described in #8 above at 900°F and a vacuum environment of 1×10^{-2} torr (~240,000 ft altitude). The lubricant-gallium/indium materials have therefore demonstrated their ability to lubricate satisfactorily in a no-moisture or vacuum environment.

IV. FUTURE WORK

During the next reporting period the material's support program will further evaluate the use of Cu-W fillers in both the WS_2-GaIn and the WSe_2-GaIn composites. Concentration, metal ratios, and pressing conditions will be studied. In addition, combinations other than Cu-W will be evaluated. In the functional test program efforts will continue to improve the life of the 204 system at 900°F by applying the composites generated by the materials program. It is also planned to continue testing at the 21,500 rpm -600°F level on the 204 system, and evaluate the effect of titanium carbide balls on the 600°F life of the 207 bearing system.

REFERENCES

1. Boes, D. J., Bober, E. S., and Grossett, K. W., "Solid Film Lubrication Research, Part I," AFAPL-TR-66-110, Part I, October 1966.
2. Boes, D. J., and Bober, E. S., "Solid Film Lubrication Research," Fourth Quarterly Report, December 1966.
3. Private Correspondence from J. S. Cunningham, December 1, 1966.
4. Boes, D. J., "New Solid Lubricants: Preparation, Properties, and Potentials for Aerospace Applications," IEEE Transactions, Vol. AS-2, No. 2, April 1964.

Table I
Effect of Lubricant Annealing Temperature and Ball-Mill Time on 80% WS_2 - 20% GaIn (wt.) Strength

Lubricant Anneal Temp - °F	Ball-Mill Time-Min.	Composite Compressive Strength-psi	1000 psi - RT μ*	wear-mgm/hr	Fabricating** Pressure-psi	Average Compressive-psi
1380	60	1950	0.06	2	50,000	
1380	60	5850	----	-	50,000	
1380	60	9150	----	-	50,000	
1380	60	9800	----	-	50,000	6687
930	60	10650	0.05	2	50,000	
930	60	5000	----	-	50,000	
930	60	5400	----	-	50,000	
930	60	3650	----	-	50,000	6180
750	60	12100	0.11	2	50,000	
750	60	13100	----	-	50,000	
750	60	13300	----	-	50,000	
750	60	12300	----	-	50,000	12700
930	15	11000	----	-	25,000	
930	15	12750	----	-	50,000	
930	15	13250	----	-	75,000	
930	15	13500	----	-	100,000	12625
750	30	15950	0.08	2	50,000	
750	30	14300	----	-	50,000	15125

*μ = Friction Coefficient

**All specimens pressed @ 75°F

Table II
Lubricating Characteristics and Compressive Strength
Modified Solid Lubricant-Gallium/Indium Composites

Composition wt%	Fabricating Pressure*-psi	Compressive Strength-psi	500 psi - 75F μ**	500 psi - 75F wear-mgms/hr
$80WS_2$*** - 20 GaIn	25000	8040	---	--
$80WS_2$*** - 20 GaIn	50000	6660	0.09	2(a)
$80WS_2$*** - 20 GaIn	75000	5420	---	--
$80WS_2$*** - 20 GaIn	100000	6020	0.10	4
$50WSe_2Gl$ - $50WS_2Gl$	25000	7490	---	--
$50WSe_2Gl$ - $50WS_2Gl$	50000	7260	0.16	2
$50WSe_2Gl$ - $50WS_2Gl$	75000	7900	---	--
$50WSe_2Gl$ - $50WS_2Gl$	100000	6584	---	--
$75WSe_2Gl$ - $25WS_2Gl$	25000	6620	---	--
$75WSe_2Gl$ - $25WS_2Gl$	50000	7440	0.16	2
$75WSe_2Gl$ - $25WS_2Gl$	75000	7030	---	--
$75WSe_2Gl$ - $25WS_2Gl$	100000	4140	---	--
$80WS_2Gl$ - 20W (325 mesh)	25000	8300	---	--
$80WS_2Gl$ - 20W (325 mesh)	50000	6220	---	--
$80WS_2Gl$ - 20W (325 mesh)	75000	8490	---	--
$80WS_2Gl$ - 20W (325 mesh)	100000	6040	---	--

(a)1000 psi - 75°F

* All specimens fabricated at room temp.

** μ = friction coefficient

***All WS_2 annealed at 930°F - Ball mill time 1 1/2 hrs.

Table III
Effect of Pressing Conditions on Metal-Filled WS_2^*-GaIn Composite Properties

A. 80% [$80WS_2$-20GI] - 20% Ta(325 mesh) wt.%

Pressing Conditions		Compressive	1000 psi - RT	
Temp -°F	Pressure-psi	Strength-psi	μ^{**}	wear-mgm/hr
75	25000	15100	-	-
75	50000	16000	-	-
75	75000	20200	0.13	2
75	100000	15100	-	-
300	25000	14600	-	-
300	50000	19900	0.10	2
300	75000	19900	-	-
500	25000	DELAMINATED UPON STRIPPING		
500	50000	18100	-	-
500	75000	17300	0.09	2

B. 80% [$80WS_2$-20GI] - 20% Mo(325 Mesh) wt.%

Temp -°F	Pressure-psi	Strength-psi	μ^{**}	wear-mgm/hr
75	25000	14600	-	-
75	50000	15050	-	-
75	75000	16500	0.06	2
75	100000	17800	-	-
300	25000	11550	-	-
300	50000	16550	-	-
300	75000	15650	0.06	4
500	25000	DELAMINATED UPON STRIPPING		
500	50000	17750	0.06	2
500	75000	DELAMINATED UPON STRIPPING		

*WS_2 Annealed @ 750°F - WS_2GI ball-milled for 30 minutes

**μ = Friction Coefficient

Table IV
Effect of Cu-W Fillers on WS_2^*-GaIn
Composite Properties

Composition wt%	Fabricating Pressure** psi	Compressive Strength-psi	1000 psi - 75°F μ	1000 psi - 75°F wear-mgm/hr
$80WS_2Gl^{***}$ - 20W	25000	16300	-	-
$80WS_2Gl^{***}$ - 20W	50000	16250	0.10	4
$80WS_2Gl^{***}$ - 20W	75000	16450	-	-
$80WS_2Gl^{***}$ - 20W	100000	15800	-	-
$80WS_2Gl$ - 20Cu	25000	13000	-	-
$80WS_2Gl$ - 20Cu	50000	15350	0.19	3
$80WS_2Gl$ - 20Cu	75000	8150	-	-
$80WS_2Gl$ - 20Cu	100000	9700	-	-
$80WS_2Gl$ - 10W - 10Cu	25000	19300	-	-
$80WS_2Gl$ - 10W - 10Cu	50000	25900	0.07	2
$80WS_2Gl$ - 10W - 10Cu	50000	23650	-	-
$80WS_2Gl$ - 10W - 10Cu	50000	24450	-	-
$80WS_2Gl$ - 10W - 10Cu	75000	20850	-	-
$80WS_2Gl$ - 10W - 10Cu	100000	23100	-	-
$80WSe_2Gl^{***}$ - 10W - 10Cu	25000	16400	-	-
$80WSe_2Gl^{***}$ - 10W - 10Cu	50000	33350	0.15	4
$80WSe_2Gl^{***}$ - 10W - 10Cu	75000	43800	-	-
$80WSe_2Gl^{***}$ - 10W - 10Cu	100000	47250	-	-

*-WS_2 Annealed @ 750°F; $80WS_2$ - 20GaIn Ball-milled 30 minutes
** μ = Friction coefficient
*** 80% lubricant - 20% GaIn (75% Ga-25% In) wt.

Table V
Effect of Temperature on Friction-Wear Characteristics[a] of Various Composites @ 80 psi-2550 fpm

Material Composition wt%	Compressive Strength-psi	75°F μ	75°F Scar-mm	600°F μ	600°F Scar-mm	900°F μ	900°F Scar-mm
$80WSe_2$ - 20 GaIn	20000[b]	0.06	3	0.04	5	0.04	11
$80WS_2$ - 20 GaIn	8000[b]	0.08	2	0.06	2 3/4	0.2[illegible]	2 3/4
$50WS_2Gl$** - 50 WSe_2GI***	7550[b]	0.15	4	0.04	3	0.20	9
$75WS_2Gl$ - 25 WSe_2GI	7030[b]	0.14	3	0.10	2 3/4	0.34	5 1/2
$90WS_2Gl$ - 10 W	7940	0.03	2 1/2	0.25	2 1/2	0.20	3
$80WS_2Gl$ - 20 W	7670[b]	0.03	2 1/2	0.22	3	0.17	3
$80WSe_2Gl$ - 20 W	16600	0.06	3	0.04	2	0.28	4 1/2
$80WSe_2GI$ - 10 W - 10 Cμ	47250	0.28	2	0.14	3 1/4	0.11	5
$80WS_2Gl$ - 10 W - 10 Cμ	24700[b]	0.31	2 1/2	0.18	3	0.32	4
Commercial A	10550	0.02	6 1/2	0.04	7 1/2	0.18	13
Commercial B	---	0.02	2 1/4	0.36	3 1/2	0.15	5 1/2
Commercial C	---	0.08	2 1/4	0.03	4 1/4	0.20	6 3/4
Commercial D	16190	0.40	2 1/2	0.32	3 1/2	0.36	5

(a) Hohman test against M-2 tool steel.

(b) Average of three tests.

* 75% Ga - 25% In (wt%)

** $80WS_2$ - 20 GI (wt%)

*** $80WSe_2$ - 20 GI (wt%)

TABLE 6-204 FUNCTIONAL TEST RESULTS BEARING SPEED - 10,600 RPM

Run No.	Load-Lbs Thrust	Load-Lbs Radial	Temp °F	Life Hrs	Ball No.	Cage Type	Cage Fit	Brg. Int. Cl-Mil	Cage Material	Unusual Test Features	Failure Mode
148	50	50	600-Air	215	8-M2	LL*	St'd**	5.5	80/20 WGI***	Double Shrouded Retainer	Pocket Wear
149	50	50	600-Air	190	8-TiC	LL*	St'd**	5.5	80/20 WGI***	TiC Balls	Pocket Wear
150	100	100	600-Air	98	8-M2	LL*	St'd**	5.5	80/20 WGI***	Test Interrupted at 70 Hrs Due to Power Failure	Cage Fracture Pocket Wear
151	50	50	600-Vac	> 50	8-M2	LL*	L10**	5.5	80/20 WGI***	Vacuum Envir. -1×10^{-2} mmHg	Radial Wts Loosened & Lost at 50 Hrs
154	50	50	900-Air	14	8-TiC	LL	L20**	5.5	80/20 WGI***	TiC Balls-Extra Loose Cage Fit	Pocket Wear
155	50	50	900-Air	4	8-M2	LL	L10	5.5	80/20 WS_2GI	WS_2 Commercial Grade	Cage Fracture
156	50	50	900-Air	1	8-M2	LL	L10	5.5	70WS_2 GI-30Ta	Metal Filler	Cage Fracture
157	50	50	900-Air	23	8-M2	LL	L10	5.5	90WS_2 GI-10W	Metal Filler	Cage Fracture
158	50	50	900-Air	2	8-M2	LL	L10	5.5	70WGI-30Ta	Metal Filler	Cage Fracture
159	50	50	900-Air	6	7-M50	LL	L10	3.5	80/20 WGI	Barden Bearing	High Pocket Wear
160	50	50	900-Air	19	6-M2	Insert	L10	5.5	80/20 WGI	Cage O.D. Reduced by 10 Mils	Pocket Wear-Loss of Inserts
152	50	50	900-Vac	66	8-M2	LL	L10	5.5	80/20 WGI	Vacuum Envir. -1×10^{-2} mmHg	Pocket Wear
161	50	50	900-Air	15	8-M2	LL	L10	5.5	80/20 WS_2GI	¥ WS_2-750C Synthesis	Cage Fracture
162	50	50	900-Air	3	7-M2	Insert	L10	5.5	80/20 WS_2GI	¥ WS_2-750C Synthesis	Loss of Inserts
171	50	50	900-Air	3	6-M2	Insert	L10	5.5	80WS_2GI-20W	Insert Type Cage	Loss of Inserts
173	50	50	900-Air	2	6-M2	Insert	L10	5.5	80WS_2GI-20W	Insert Type Cage	Loss of Inserts
174	50	50	900-Air	0.05	8-M2	LL	L10	5.5	Boron Nitride	BN as Self-Lube Cage	Rough Operation-High Wear
175	50	50	900-Air	0.5	8-M2	No Shroud	L10	5.5	Graphite-Sk-267	Carbon-Graphite as Lube	Cage Fracture
167	50	50	900-Air	0.5	8-M2	LL	L10	5.5	Graphite-Sk-267	Carbon-Graphite as Lube	Shrouds Loosened at Temperature
177	50	50	900-Air	20	8-TiC	LL	L10	5.5	Graphite-Sk-267	Pinned Shroud	Cage Fracture
178	50	50	900-Air	5	8-M2	LL	L10	5.5	80WS_2GI-20W		Rough Operation
179	50	50	900-Air	19	8-M2	LL	L10	5.5	80/20WS_2GI (400C)	¥ WS_2 - 400C Synthesis	Cage Fracture
180	50	50	900-Air	3	8-M2	LL	L10	5.5	80WGI-20W		Cage Fracture-Pocket Wear
181	50	50	900-Air	16	8-M2	LL	L10	5.5	80/20WS_2GI (500C)	¥ WS_2 - 500C Synthesis	Cage Fracture
182	50	50	900-Air	4	6-M2	Insert	L10	5.5	80WS_2GI-20W	Insert Type Cage	Loss of Inserts
183	50	50	900-Air	25	8-M2	LL	L10	5.5	75WS_2GI-25WGI	WS_2-WSe_2 Lubricant Mix	Rough Operation-Cage Wear
184	50	50	900-Air	25	8-M2	LL	L10	5.5	80 [50/50WS_2GI-WGI] - 20W	WS_2-WSe_2 Lubricant Mix	Rough Operation-Cage Wear
185	50	25	900-Air	19	8-M2	LL	L10	5.5	50WS_2GI-50WGI	WS_2-WSe_2 Lubricant Mix	Cage Wear
186	50	50	900-Air	16	7-M2	Insert	L10	5.5	80/20WS_2GI	Inserts Locked into Cage	Ball Insert Fracture
187	50	50	900-Air	6	6-M2	Insert	L10	5.5	80/20WS_2GI	Inserts Locked into Cage	Ball Insert Fracture

* Double L Type Titanium Shroud

** St'd Fit - 0.010" Clearance Between Ball & Pocket - 0.008" Clearance Between Cage & Inner Race
L10 Fit - 0.020" Clearance Between Ball & Pocket - 0.018" Clearance Between Cage & Inner Race
L20 Fit - 0.030" Clearance Between Ball & Pocket - 0.018" Clearance Between Cage & Inner Race

*** WGI - 80% WSe_2-20% GaIn

Dwg. 4500497

TABLE 7–204 FUNCTIONAL TEST RESULTS 21,500 RPM - 600°F - 50LBS THRUST/50LBS RADIAL

Run No.	Life Hrs.	Ball No.	Cage Type	Cage Fit	Brg. Int. Cl-Mils	Cage Material	Unusual Test Features	Failure Mode
163	5 Sec	8-M50	No Shroud	St'd**	3.5	80/20 WGI***	Outer Race Riding-Barden Brg.	Immediate Cage Fracture
164	5 Sec	8-M50	No Shroud	L10**	3.5	80/20 WGI***	Outer Race Riding-Barden Brg.	Immediate Cage Fracture
153	0.1	8-M2	LL*	L10**	5.5	80/20 WGI***	Vacuum Envir. - 2×10^{-2} mmHg	Test Stopped Purposely
165	2.7	8-TiC	LL*	St'd	5.5	80/20 WGI***	TiC Balls	Fracture of one Pocket Bridge
172	0.1	8-TiC	LL*	St'd	5.5	Graphite-Sk-267	TiC Balls-Graphite Cage	Shrouds Loosened on Retainer-Ball Contact
168	3.5	8-M50	LL*	St'd	3.5	80/20 WGI	Barden Bearing	Pocket Wear-Cage Instability
169	2.0	8-TiC	LL*	St'd	5.5	80/20 WGI	Barden Bearing	Cage Instability
170	0.6	7-TiC	LL*	L10	5.5	80/20 WGI	Brazed Shroud	Cage Instability
176	0.5	8-TiC	LL*	L10	5.5	Graphite-Sk-267	Pinned Cage	Cage Fracture

* Double L Type Titanium Shroud

** St'd Fit - 0.010" Clearance Between Ball & Pocket - 0.008" Clearance Between Cage & Inner Race
L10 Fit - 0.020" Clearance Between Ball & Pocket - 0.018" Clearance Between Cage & Inner Race

*** WGI - 80% WSe_2 - 20% GaIn

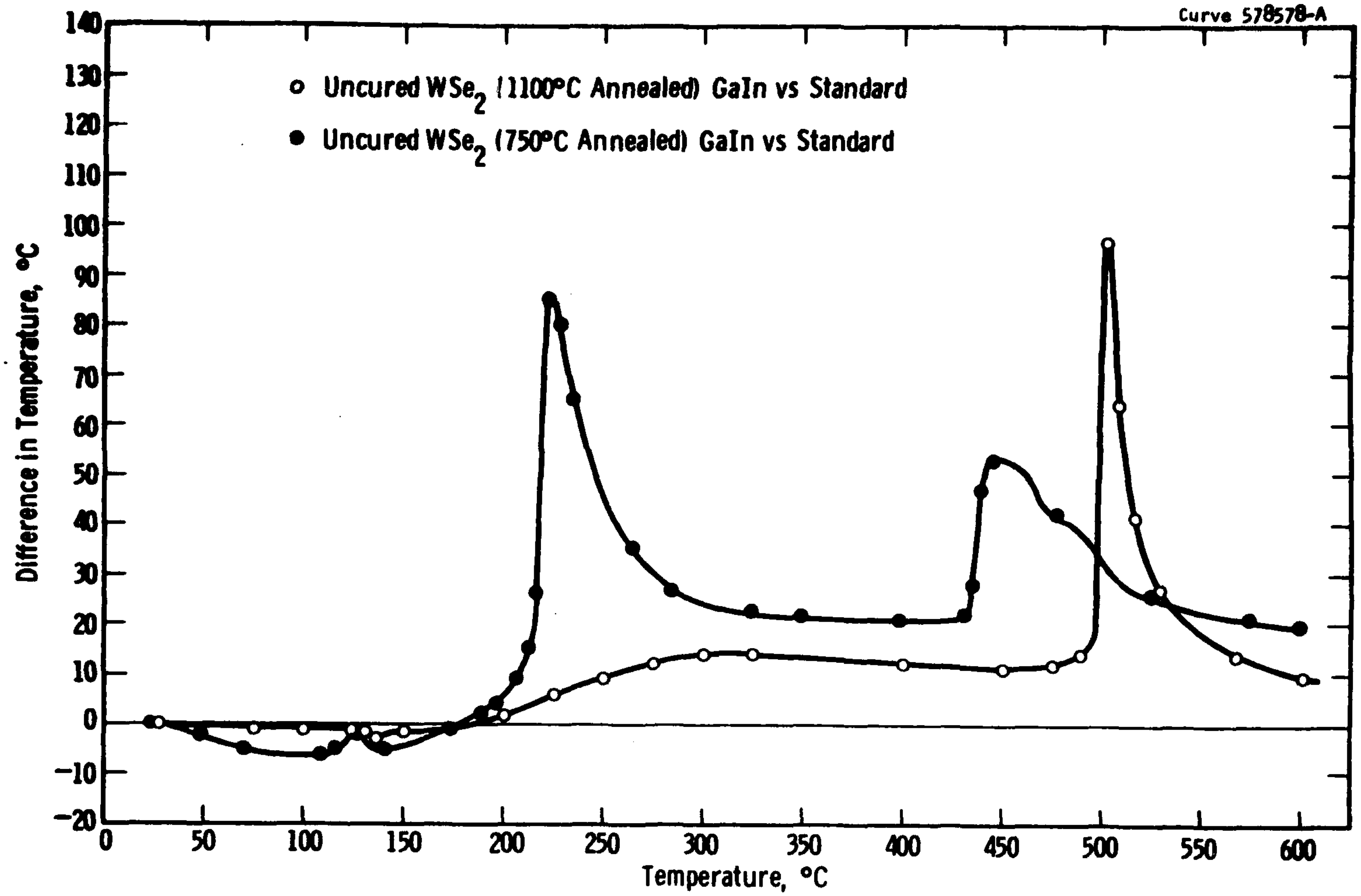

Fig. 1 -DTA - uncured 80 (1100° annealed WSe_2) 20 GaIn (75/25)

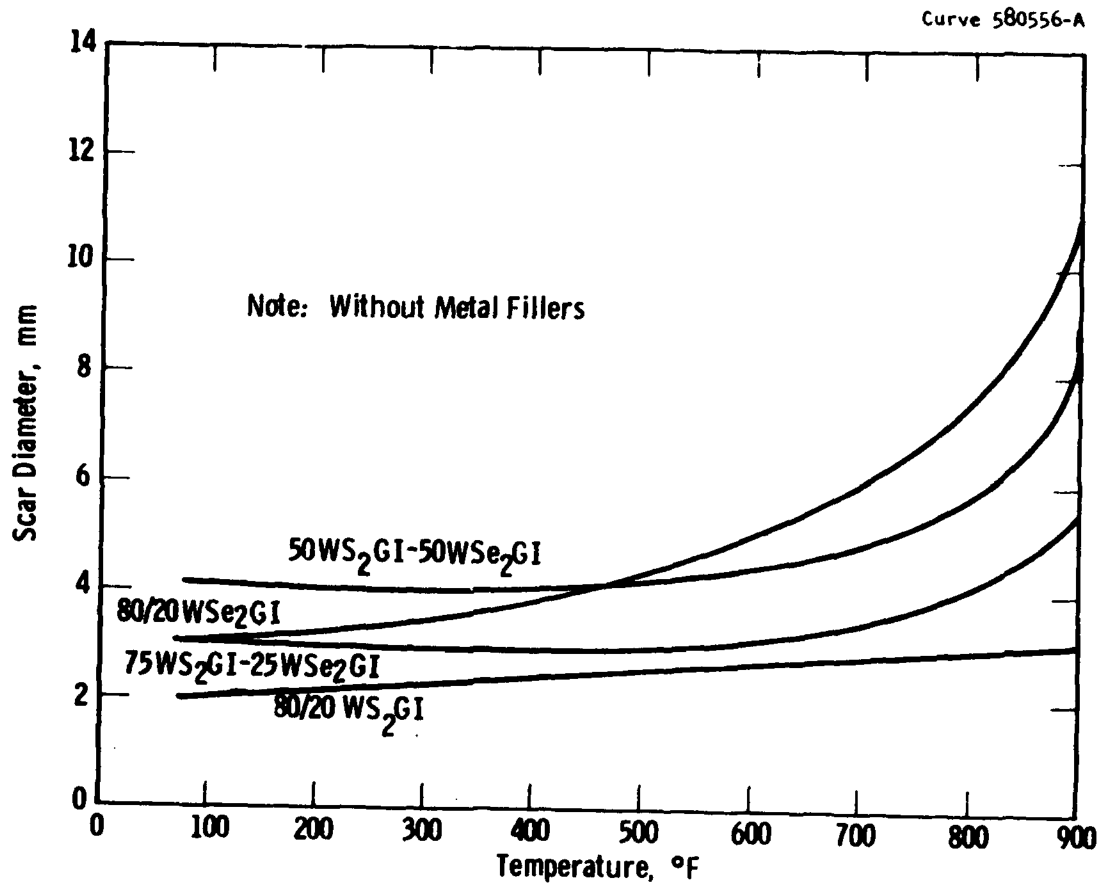

Fig. 2—Effect of temperature on unfilled composite wear resistance at 80 psi-2550 fpm

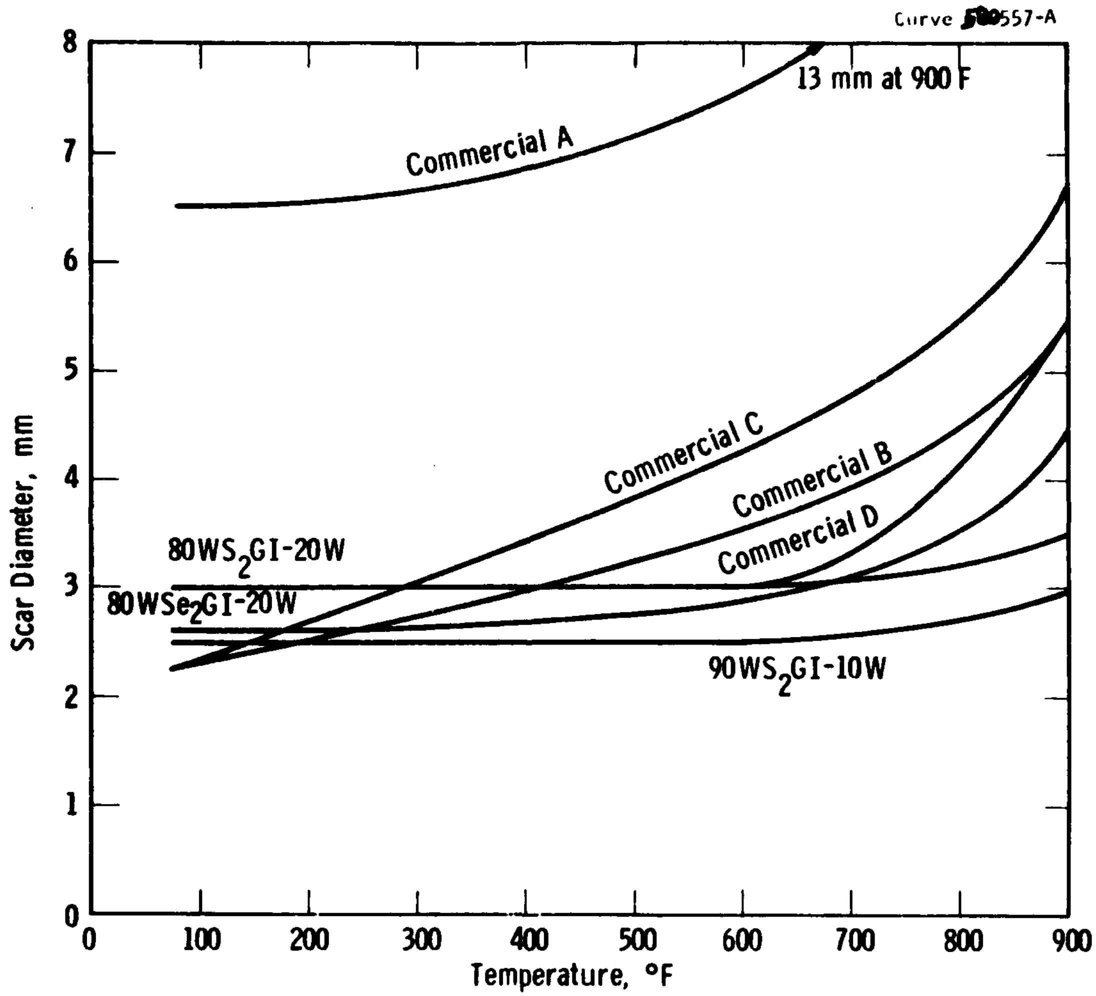

Fig. 3—Effect of temperature on metal-filled composite wear resistance at 80 psi-2550 fpm

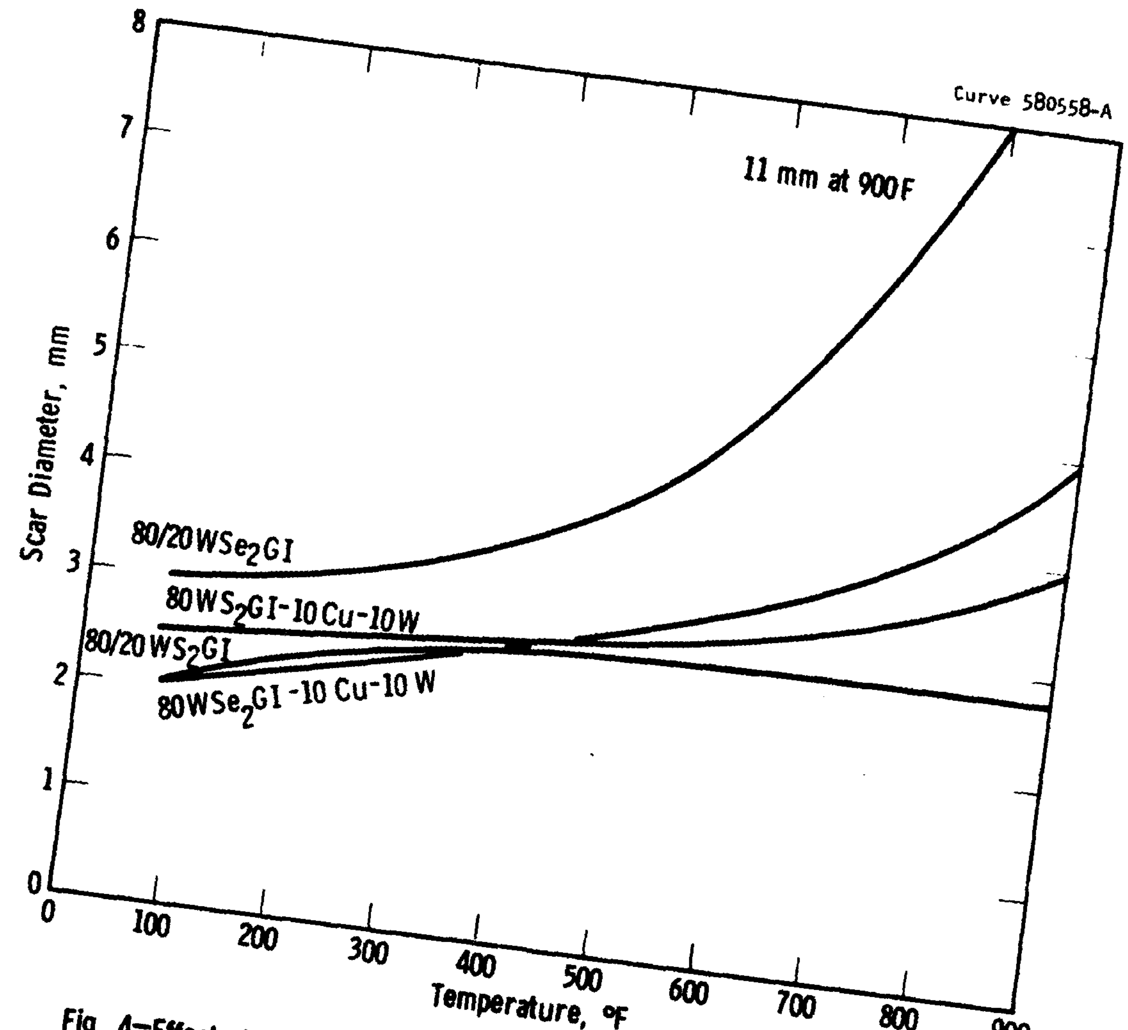

Fig. 4—Effect of temperature on composite wear resistance at 80 psi-2550 fpm

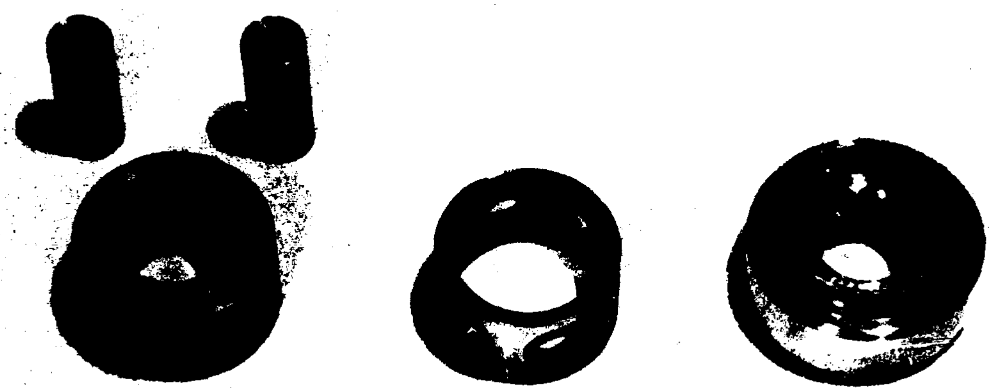

FIGURE 5 Left - Tungsten Diselenide-Gallium Indium Blank for 204 Size Bearing

Middle - Titanium Retainer with Self-Lubricating Inserts

Right - 204 Size Ball Bearing Equipped with Titanium Retainer

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FIGURE 6 *Left* - Tungsten Diselenide-Gallium Indium Blank for 204 Size Bearing

Middle - Double, Titanium Shrouded Retainer Machined from Blank

Right - 204 Size Ball Bearing Equipped with Shrouded Retainer

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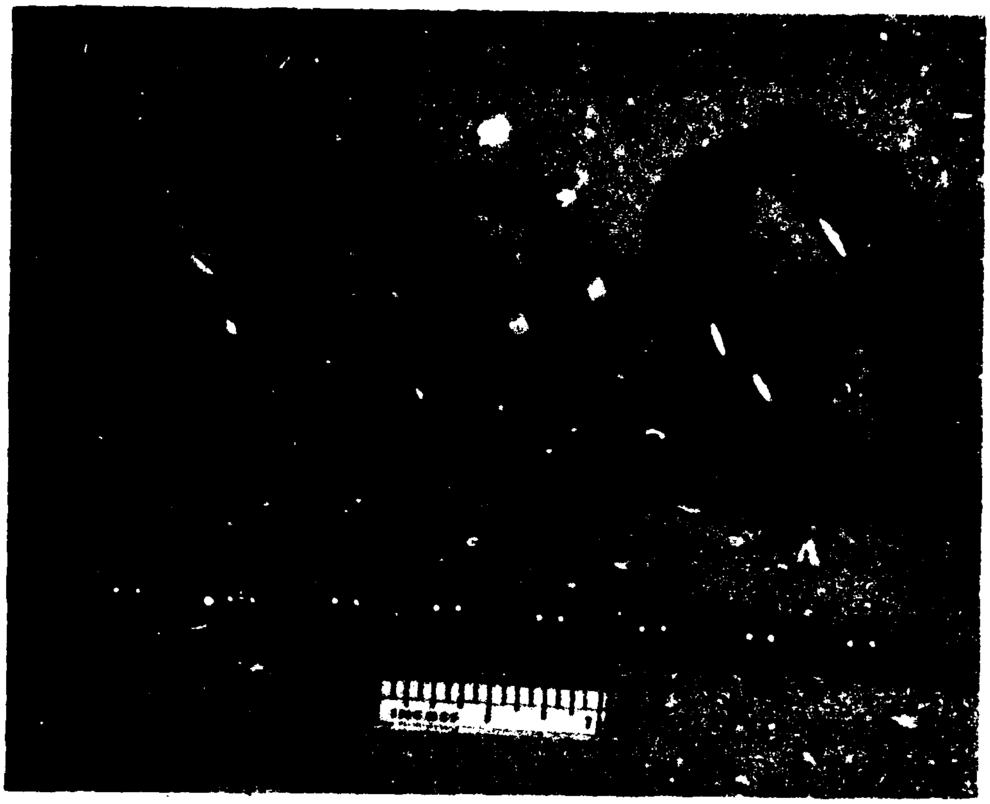

Fig. 7—Size 204, Run #148 - 215 hrs. at 10,600 rpm, 50# thrust/50# radial, 600°F, air atm.

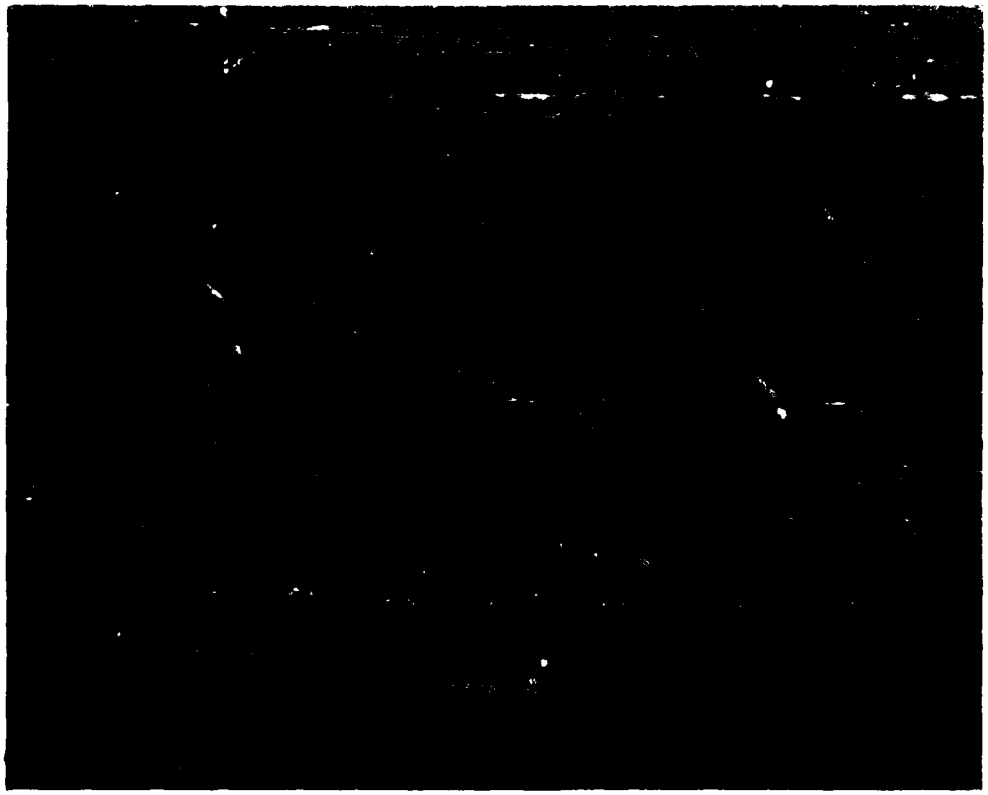

Fig. 8—Size 204, Run #149 - 190 hrs. at 10,600 rpm, 50# thrust/50# radial, 600°F, air atm.

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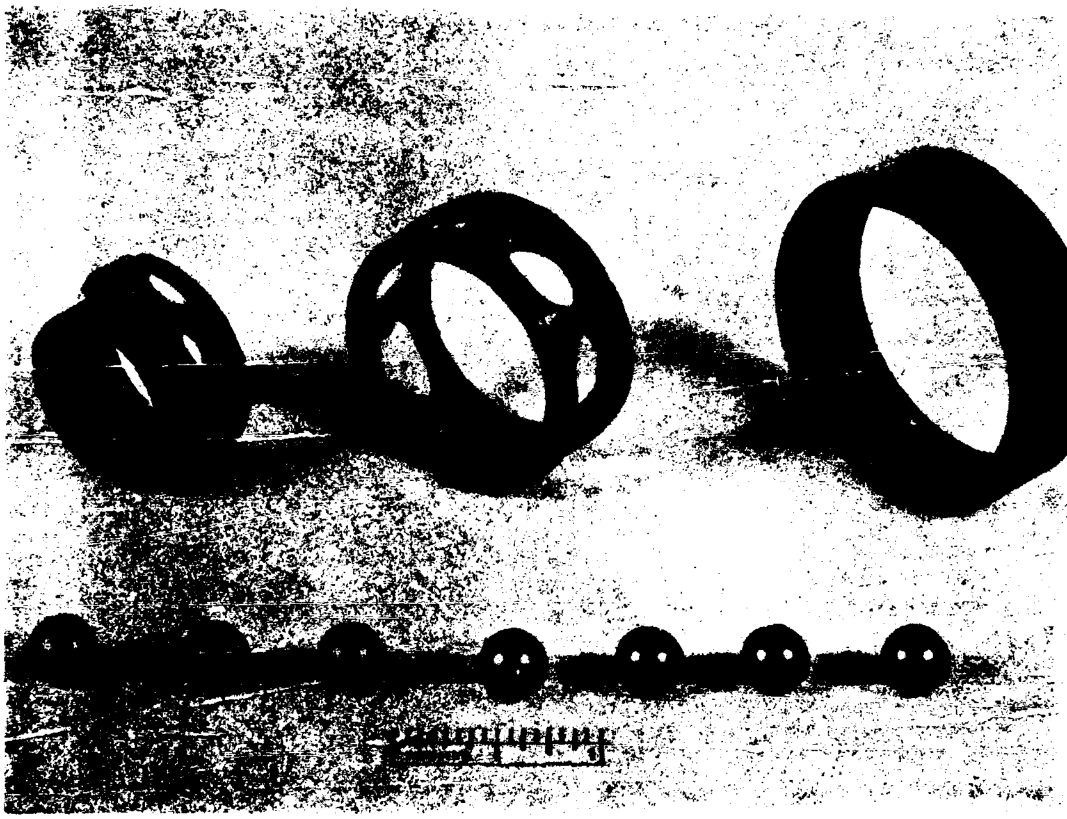

Fig. 9—Size 204, Run #168 - 3.5 hrs. at 21,500 rpm
50# thrust/50# radial, 600°F, air atm.

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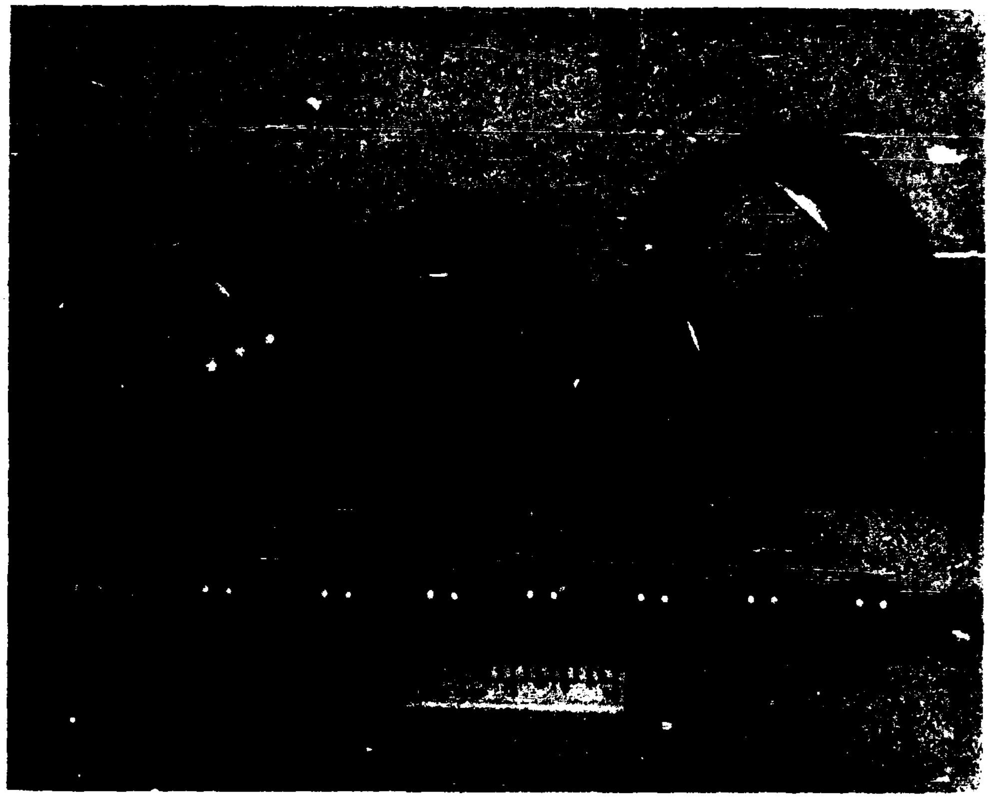

Fig. 10—Size 204, Run #165 - 2.7 hrs. at 21,500 rpm,
50# thrust/50# radial, 600°F, air atm.

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13 ABSTRACT

This report describes progress during the seventh quarterly period in a program designed to develop a solid film lubricated ball bearing system capable of operation under high speed, high temperature oxidizing conditions. The program's ultimate goal is long-term ball bearing operation at 1500°F and speeds of 10,000 to 30,000 rpm under atmospheric conditions simulating sea-level to 200,000 ft altitudes. A second program objective is to provide parametric design data relating the operating life, load, bearing size, speed, temperature and environment of these bearing systems.

In the materials development area, this report describes further efforts in improving the high temperature friction-wear characteristics of unique self-lubricating composites that are both physically and chemically capable of functioning as load-bearing surfaces in an extreme temperature-oxidizing environment. The composites are composed of solid lubricants, such as WSe_2 and/or WS_2 that have been combined with a gallium-indium alloy.

In the area of functional testing, the results of thirty-nine tests on 204 ball bearings that were evaluated during this reporting period are described. The bearings were operated at temperatures up to 900°F and speeds of 10,600 and 21,500 rpm. Two significant results obtained during this reporting period are the operation of (1) a 204 ball bearing in 600°F-air at 10,600 rpm for a period of 215 hours, and (2) an identical bearing system at 10,600 rpm in a 900°F environment simulating an altitude of 240,000 ft for 66 hours. In both cases the bearing carried a 50 lb thrust/50 lb radial load.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Gallium						
Indium						
High temperature						
Oxidation						
Friction						
Wear strength						
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